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Classifying and characterising fine-grained soils using fall cones

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Abstract: Soil classification tests (liquid and plastic limits) are the most common tests performed in geotechnical engineering practice. In 'data poor' regions that are also vulnerable to natural hazards, they are often the only information engineers have available to assign parameters for geotechnical modelling and assessment purposes. This paper presents a review of some key correlations that rely on these data and summarises some recent research findings regarding the relationship between liquid limits measured using the Casagrande cup and fall-cone approaches, including the effect of different base hardness for the Casagrande cup device.

Keywords: Atterberg limits; Casagrande cup; Fall cones; Geotechnical correlations

1 INTRODUCTION

The Atterberg limits are the most common soil tests conducted in geotechnical engineering laboratories around the world. Atterberg (1911a, 1911b) originally proposed seven limits (state transitions), three of which remain in widespread use today: namely, the liquid limit (w_L), the plastic limit (w_P) and the shrinkage limit (w_S). This review paper focuses on the liquid and plastic limits, which are used for soil classification purposes and also in the myriad of correlations that have been built up with other geotechnical parameters over the decades. The plastic limit is determined using the standard thread rolling test, which measures the onset of soil brittleness associated with cavitation of the pore fluid or air entry (Haigh et al. 2013). The liquid limit is invariably determined using the Casagrande cup (Casagrande 1932) or the fall-cone (e.g., BS 1377-2) device. However, the discontinuation of the Casagrande cup method has been advocated by many researchers, including Casagrande (1958), Kazama and Shimobe (1997) and Shimobe (2010). This paper summarises some recent research findings on the classification and characterisation of fine-grained soils using the fall-cone approach. A more in-depth review of the use of fall cones to determine Atterberg limits has recently been published (O'Kelly et al. 2018), on which some of the work presented in this paper is based.

2 USE OF ATTERBERG LIMITS IN GEOTECHNICAL CORRELATIONS

Geotechnical practitioners have long relied on correlations between basic soil properties and more complex ones, with the Atterberg limits often employed for this purpose. For instance, Kulhawy and Mayne (1990) published a manual reporting many correlations that can be used to estimate parameter values pertinent for foundation design. Kenny (1959), Brooker and Ireland (1965), Ladd et al. (1977) and Sørenson and Okkhels (2013) all linked the effective peak friction angle to the plasticity index ($I_P = w_L - w_P$). Sørenson and Okkhels (2013) also give a correlation linking the peak effective friction angle for normally consolidated soil (ϕ'_{nc}) with the plasticity index (Eq. 1), while Carrier and Beckman (1984) linked the liquidity index (Eq. 2) with the permeability coefficient (k) and void ratio, e (Eq. 3).

$$\phi'_{nc} = 43 - 10\log(I_P) \quad \text{(deg.)} \qquad R^2 = 0.41, n = 233 \tag{1}$$

$$I_L = \frac{w - w_P}{w_L - w_P} \tag{2}$$

$$I_L = 95.21[k(1+e)]^{0.233} - 0.242 \qquad (k \text{ is in m/s}) \tag{3}$$

While some of these correlations have some basis in the mechanics of the liquid limit tests, others are merely statistical correlations. Hence, the use of these correlations, which may have been extrapolated beyond their original datasets, is worthy of further consideration.

2.1 Fall-cone undrained strength variation with liquidity index

Hansbo (1957) presented the formula given in Eq. (4) to calculate the undrained shear strength of soil from data obtained using a fall-cone device (i.e. c_{uFC}).

$$c_{uFC} = \frac{KW}{d^2} \tag{4}$$

where K is a cone factor, W is the cone weight and d is the cone penetration into the soil specimen.

Based on an examination of previously published undrained strengths at the liquid limit (i.e. c_{uL}) and using the assumption from Schofield and Wroth (1968) of a 100 fold increase in the undrained strength over the plastic range, Wroth and Wood (1978) suggested an equation of the form given here as Eq. (5) for deducing the undrained strength corresponding to any water content within the plastic range. Similarly, this equation has been employed to deduce the fall-cone undrained strength (i.e. c_{uFC}=c_u) corresponding to a given water content value.

$$c_u = c_{uL} {R_{MW}}^{(1-I_L)} \tag{5}$$

where c_{uL}=1.7 kPa and the factor increase in undrained strength over the plastic range (R_{MW}) was taken as 100 (Wroth and Wood 1978).

This assumption of an R_{MW} value of 100 has been retained by some researchers seeking to use fall-cone test data to estimate the plastic limit (e.g., Sharma and Bora, 2003), although an essentially different parameter is measured taking this approach; that is the plastic strength limit (PL_{100}) (Haigh et al. 2013; Stone and Phan 1995). Adaptations of the standard fall-cone setup have been proposed for determining the values of c_{uFC} for lower liquidity index, thereby allowing the establishment of the PL_{100} value from the regression line). For instance, one such approach is the fall-cone device incorporating a 200-mm falling distance before the cone tip contacts the top surface of the test specimen, as presented in Sivakumar et al. (2015).

Vardanega and Haigh (2014) compiled a database of 641 fall-cone tests on 101 soils and computed a value of 34.3 for R_{MW} (Eq. 6). Other researchers have also reported values for R_{MW} lower than 100; e.g., Whyte (1982) suggested a value of approximately 70. Reporting on the fall-cone strength testing of municipal sludge and residue materials, O'Kelly (2018) noted that compared with most inorganic soils, these materials have much higher strain rate dependence, which must be accounted for in the K value employed for strength calculations using Eq. (4).

$$c_{uFC} = c_{uL}(34.3)^{(1-I_L)} \qquad \text{for } 0.2 < I_L < 1.1 \text{ and where } c_{uL} = 1.7 \text{ kPa} \tag{6}$$

2.2 Fall-cone undrained strength variation with liquidity index

Koumoto and Houlsby (2001) suggested that logarithmic liquidity index (Eq. 7) is superior to liquidity index (Eq. 2) (although they also used the assumption that R_{MW} = 100) in considering correlations with undrained shear strength.

$$I_{LN} = \frac{\ln(w/w_P)}{\ln(w_L/w_P)} \tag{7}$$

Vardanega and Haigh (2014) used their fall-cone database to derive Eq. (8), which also has a good statistical fit to the database (as does Eq. 6), but it does have the advantage of reducing some of the scatter at the extremities of the data set studied.

$$c_{uFC} = c_{uL}(83.5)^{(1-I_L)} \quad \text{where } c_{uL} = 1.7 \text{ kPa} \tag{8}$$

3 COMPARISON OF FALL-CONE LIQUID LIMIT WITH CASAGRANDE LIQUID LIMIT

Fig. 1 shows the comparison of the liquid limit derived using the Casagrande cup method with that derived using the fall-cone method from various researchers and publications. There have been various attempts to link the fall-cone and Casagrande cup liquid limits; e.g., Özer (2009). Most recently, O'Kelly et al. (2018) produced the Eqs (9)–(12) linking the liquid limits deduced using the 80g–30° fall cone ($w_{L,FC}$) with those derived from the British Standard ($w_{L,BS\ cup}$: see BS 1377-2) and the ASTM Standard (i.e. $w_{L,ASTM\ cup}$) Casagrande cup devices. This division of the database is needed as the effect of the different base hardness between these standardised cup devices can be significant for the computed liquid limit value (see Section 4).

$$w_{L,FC} = 1.86\left[w_{L,BS\ cup}\right]^{0.84} \quad \text{(for } w_L \text{ values of up to} \sim 600\%) \quad R^2 = 0.98,\ n = 216 \tag{9}$$

$$w_{L,FC} = 1.62\left[w_{L,BS\ cup}\right]^{0.88} \quad (w_{L,BS\ cup} < 120\%) \quad R^2 = 0.96,\ n = 199 \tag{10}$$

$$w_{L,FC} = 1.90\left[w_{L,ASTM\ cup}\right]^{0.85} \quad \text{(for } w_L \text{ values of up to} \sim 600\%) \quad R^2 = 0.97,\ n = 199 \tag{11}$$

$$w_{L,FC} = 1.45\left[w_{L,ASTM\ cup}\right]^{0.92} \quad (w_{L,ASTM\ cup} < 120\%) \quad R^2 = 0.97,\ n = 188 \tag{12}$$

From Eqs (9)–(12): up to liquid limit values of around 120%, there is generally reasonable agreement between the values deduced using the fall-cone and Casagrande cup approaches, although the computed regression relationships have a degree of non-linearity. As liquid limit increases, however, the divergence between the cone and cup derived liquid limit values increases, with the cup approach tending to give higher liquid limit values (see O'Kelly et al. 2018 for further details). Haigh (2012), based on an analysis of the Casagrande liquid limit test, showed that while the fall-cone liquid limit is associated with undrained strength, the Casagrande cup liquid limit is associated with a ratio of undrained strength to soil density (i.e. specific strength). As the density at liquid limit is lower for soils having a high liquid limit than for lower plasticity soils, this deviation of the cone and cup liquid limits can be predicted.

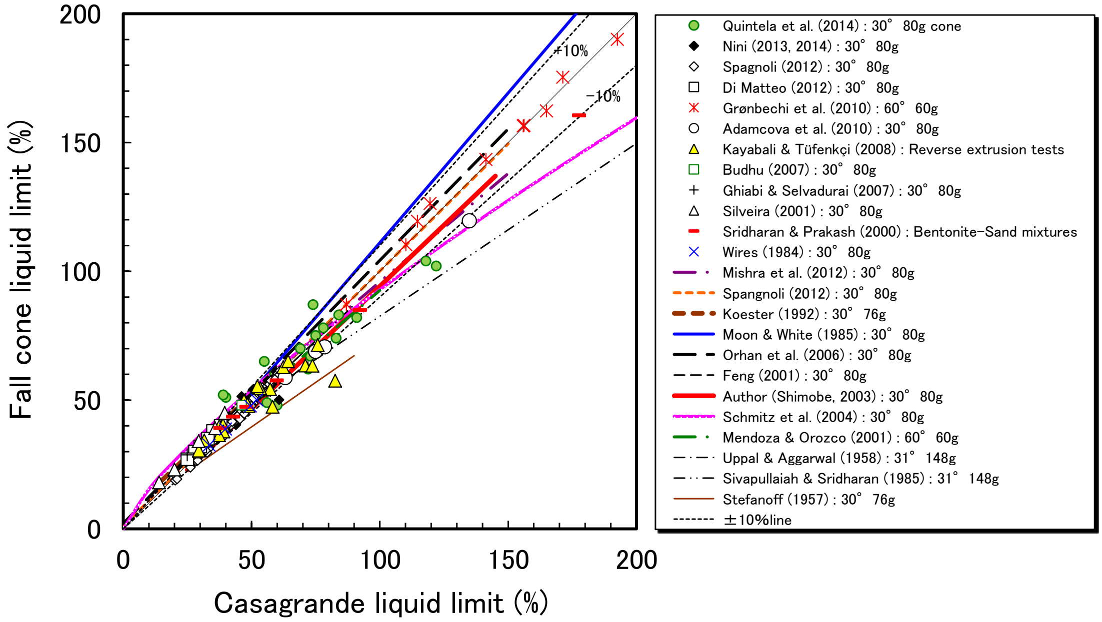

Figure 1. Fall-cone liquid limit versus Casagrande liquid limit (NB. data attributed to Stefanoff 1957 was obtained from Wasti 1987).

4 EFFECT OF BASE HARDNESS ON CASAGRANDE LIQUID LIMIT

Casagrande (1958) suggested that given little standardisation of the cup device was undertaken (which remains the case to the present day), its use for geotechnical engineering practice should be discontinued in favour of the fall-cone approach. Haigh (2016) reported on the significant difference in liquid limit values deduced for the soft and hard base materials employed in different Casagrande cup setups – noting that some codes of practice (e.g. New Zealand and Switzerland) give no advice regarding how hard the base material should be. Combining the data from Norman (1958), Sridharan and Prakash (2000) and Dragoni et al. (2008), Haigh (2016) produced Eq. (13) that links liquid limit values deduced using cup devices having hard and soft base materials (that is $w_{L,hard}$ and $w_{L,soft}$, respectively). Further, Haigh (2016) used Eq. (6) and the results of the Nemarkian analysis reported in Haigh (2012) to derive Eq. (14) which was noted to agree well with Eq. (13).

$$w_{L,hard} = 0.904[w_{L,soft}] + 0.44\% \quad \text{for } n = 35 \tag{13}$$

$$w_{L,hard} = 0.845[w_{L,soft}] + 4.7\% \tag{14}$$

5 CONCLUSIONS

This paper has summarised some recent developments in the use of the Atterberg limits for compiling geotechnical correlations. The Eqs (9)–(12) from O'Kelly et al. (2018), which reveal good overall agreement of the liquid limit deduced using the fall-cone and Casagrande cup devices for $w_L < 120\%$, are supported by additional collected data in the present investigation. The deviation of these two measurement techniques for higher liquid limit values, as predicted by Haigh (2012), is noted. While these two measurement techniques can be correlated with one another, because of the lack of standardisation of base hardness, the authors recommend that the Casagrande cup approach should be discontinued in geotechnical engineering practice in favour of a standardised fall-cone method.

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